STATEMENT OF WORK

For

COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT

Between

The United States Environmental Protection Agency

National Exposure Research Laboratory (NERL)
Exposure Methods and Measurement Division (EMMD)

National Risk Management Research Laboratory (NRMRL)
Air and Energy Management Division (AEMD)

And

Aeroqual Ltd

Title of Project
Development and Application of Low-Cost Sensors to Support Improved Air Quality Measurement and Characterization

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Period of Performance
5 years

INTRODUCTION

Criteria air pollutants including ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter (PM) and lead (Pb) are regulated as National Ambient Air Quality Standards (NAAQS) under the Clean Air Act. Significant progress has been made to improve air quality under the Clean Air Act however the need to accurately characterize air quality continues to be a challenge. While traditional methods such as Federal Reference and Equivalent Methods (FRM/FEM) have been the hallmark of air quality monitoring, these methods are costly and do not provide the spatial and temporal resolution to adequately characterize changes in pollutants in the atmosphere. Numerous advances in air quality measurement approaches have been made giving rise to what is commonly referred to as 'Next Generation Air Monitoring' (NGAM) tools as well as Next Generation Emission Measurement (NGEM) tools. Low-cost sensors are one such tool that have rapidly emerged over the years and are capable of measuring a variety of air pollutants including O_3, NO_2, SO_2, PM and many others. Sensors have the potential to be used in a variety of applications such as outdoor and indoor air pollution monitoring, near source or fence line monitoring, personal exposure monitoring, and community and individual monitoring [Snyder et al, 2013; Kumar et al, 2015].

Over the past few years, the EPA has been actively involved in evaluating sensor performance; developing and testing customized sensor devices; publishing reports and guidance documents for sensor users and developers; convening sensor developers, sensor users, and other stakeholders to discuss opportunities and challenges; and investigating possible applications of sensors such as community monitoring and citizen science activities. A number of these activities are published on EPA's Air Sensor Toolbox for Citizen Scientists, Researchers and Developers website (www.epa.gov/air-sensor-toolbox).

In its quest for a more complete understanding of the performance of ambient air quality monitoring devices in different applications, EPA will invite sensor manufacturers to collaborate individually with the agency under its research and development authorities. Direct collaboration, like through a cooperative research and development agreement under 15 U.S.C. § 371a can also bring about further development of the technology, which the collaborator can market for a wider public benefit. One such effort will be with Aeroqual Ltd, which has developed and tested a variety of sensor products that are being used worldwide. Of sensor technologies currently available, those developed by Aeroqual Ltd particularly the O_3 sensor are among the leading technologies in terms of performance and accuracy [Lin et al, 2015; Bart et al, 2014; Williams et al, 2013; Williams et al, 2009]. While much knowledge has been gained on sensor devices as a whole, there is still a need to understand the performance of sensors and explore potential applications of these emerging technologies. The rise of smaller, cheaper, and more portable air measurement technologies can provide unique opportunities to enhance and broaden air quality measurements and engage a variety of groups to inform on air quality.

GOAL

This CRADA project between the EPA and Aeroqual Ltd (herein referred to as Aeroqual) will combine expertise in ambient air measurements and sensor development to investigate new applications, methodologies and technologies for the low-cost measurement of criteria pollutants and other pollutants in ambient air. This project is anticipated to address many areas of need in sensor technology research to ultimately support improved air quality measurements and characterization. Some of these areas of need include:

- *Sensor performance*: Many sensors have shown promise in obtaining accurate and reliable air quality measurements. There is still a need to understand long-term performance and stabilty of sensors, cross-interferences with other pollutants, impacts from temperature and humidity, and performance in areas with poor air quality. Given the possible ways that data from sensor technologies can be used (e.g. supporting regulatory measurements, health/exposure metrics and other uses) ensuring long-term sensor performance is critical.
- *Sensor calibration*: The majority of sensor devices are calibrated by the manufacturer/developer only and must be replaced within 1-2 years of use. There is a need to gain more insight on into the transferability of sensor calibration for sensor users. Calibration is key for ensuring accurate and precise measurements of these technologies over time.
- *Expanding and enhancing measurement capabilities*: Most of the commercially available sensors target criteria air pollutants (e.g. PM, NO_2, O_3, and others). The ability to measure different air pollutants such as volatile organic compounds and air toxics has been of interest for a number of specific applications such as fenceline monitoring of industrial operations and individual/community air monitoring. In addition, improving existing low-cost methods for measuring pollutants is advantageous. Enhancing measurement methods and investigating new sensor technologies that target a variety of pollutants for different applications is important.
- *Sensor applications*: There are a host of applications for sensors some of which have yet to be explored or identified. Sensors can provide a unique niche in helping to improve air quality characterization, identifying hotspots or fugitive emissions, siting of regulatory air monitoring stations, and measuring air quality in environments in which it would be difficult to use traditional air monitoring methods. Investigating different applications is also important as it will allow for exploring how sensor designs can be optimized to improve measurements and increase usability.

This project will provide valuable insights on low-cost sensor technologies and applications and those insights are anticipated to transfer to sensor manufacturers/developers, researchers, users (citizen scientists, individuals, community groups, etc.), and other stakeholders.

APPROACH

This CRADA project will focus on evaluating sensor design, calibration methods and field testing of both existing low-cost sensor devices and prototype sensor devices for the measurement of a variety or pollutants. Communicating the results is a critical component of this project to help advance knowledge in air sensor research and applications. This project is composed of three (3) specific tasks which are described in more detail below.

Task 1: Evaluating Design, Field Performance and Calibration of Low-Cost Sensor Devices

Research Motivation: Many low-cost sensor devices can adequately measure air pollutant concentrations. However, there is still a need to understand long-term (6 months or more) performance and stability of sensors, cross-interferences with other pollutants, impacts on measurements due to variations in environmental conditions (e.g. hot or cold temperatures, low and high humidity, etc.), and performance in environments with either poor air quality or air pollution events such as wildfires. To understand performance especially in the field, it is critical to pair sensor devices with high quality regulatory or research grade measurement instruments for comparison. Calibration continues to be a key challenge for low-cost sensor designs. Sensor devices are normally calibrated initially in a laboratory setting by the manufacturer/developer and the transferability of such calibration to a user is not easily established. A limited number of sensor technologies offer the ability for a user to calibrate the device in the field however most sensors do not have this capability and must be replaced after 1-2 years. This presents a challenge because it is difficult to determine how a sensor is performing over time and necessitates collocating a sensor with regulatory/research grade measurement equipment to ensure data accuracy. Calibration is also important depending on the levels of air pollution in a given area. The frequency of and settings for calibration may be vastly different in areas with relatively clean air versus areas with more polluted air.

The design of the sensor technologies continuously evolves and often relies on the application of the technology as well as the end-user of the technology. Ideally, the devices have to be flexible and tailored to specific applications. This research will improve sensor-based instrument design and usability and lead to better field performance of such devices.

This task will address the following areas:

- *Sensor Design*
    - Optimizing sensor-based instrument design for different applications ranging from research to citizen science/community projects.
- *Performance*
    - Side-by-side comparison of sensors with high quality, regulatory and research grade measurements to evaluate sensor performance.
    - Understanding how sensors perform in more polluted air. Previous testing of Aeroqual sensors has been conducted in locations with relatively clean air (e.g. New Zealand and Australia). This task will allow for testing sensors in more polluted environments and gaining information on sensor calibration needs and performance.
    - Testing sensor devices under different environmental conditions (e.g. extremely cold or warm temperatures) to evaluate performance.
    - Understanding cross-interferences among pollutants in differing ambient air mixtures.
- *Calibration*
    - Studying the transferability of laboratory sensor calibration to the field and developing approaches that achieve better measurement outcomes in terms of reliability and accuracy. The low-cost sensors developed by Aeroqual are unique in that they have built in calibration tools and associated calibration equipment that will facilitate activities under this task.
- *Sensor Applications*

- Exploration and testing of applications of sensor technologies (e.g. near-source environments, community monitoring, integrating sensor measurements with other advanced monitoring methods such as satellites and remote sensing).

Methods: Sensor technologies from Aeroqual such as the SM50, S500, AQY and AQS, and others will be deployed in the field alongside traditional measurement methods (e.g. Federal Reference and Equivalent Methods and other standard methods) at dedicated air quality research sites, state/local regulatory monitoring stations, and/or in field studies. In conjunction with field testing, the design of the sensors will be evaluated and improvements in the technologies will be investigated and implemented as feasible. Calibration approaches for the sensor technologies will also be evaluated to understand how these methods can be optimized for different applications to increase reliability, accuracy, and ease of operation.

Potential monitoring sites and/or field studies for evaluating sensor design and performance are described below. Other field deployment opportunities will be identified and considered as feasible.

Air Measurement Research Sites: EPA manages the Ambient Monitoring Innovative Research Station (AIRS) site located on EPA's campus in Research Triangle Park, North Carolina. This site contains a suite of instrumentation for continuous measurement of ambient air pollutants (O_3, NO_2, SO_2, CO, PM and formaldehydye) and column trace gases and aerosols. AIRS is regularly used by EPA to evaluate the performance of FRM/FEM instruments, other traditional air quality methods, and emerging measurement technologies (e.g. low-cost sensors, remote sensing) under real-world conditions. A similar research site was developed at the NASA Langley Research Center in Hampton, Virginia called the Chemistry and Physics Atmospheric Boundary Layer Experiment (CAPABLE). This site provides comparable measurements as EPA's AIRS site and is used by EPA to collect long-term measurements to compare surface measurements, column observations and satellite air quality measurements.

State/Local Regulatory Monitoring Sites: EPA in cooperation with the North Carolina Department of Environment and Natural Resources (NCDENR) manages the Raleigh Multi-Pollutant Site which is located adjacent to a major highway (Interstate-40) in Raleigh, North Carolina. This site represents a near-source location and is available to EPA researchers to evaluate emerging sensor technologies and other measurement methods. EPA is planning to build a long-term sensor testing shelter at this location.

Potential Field Evaluation Opportunities:

- *Fenceline Monitoring Project in Louisville, Kentucky*: This study will take place from summer 2017 to summer 2018 in the 'Rubbertown district' in Louisville, Kentucky as part of a Regional Applied Research Effort (RARE) Project with EPA Region 4. The Rubbertown district has a large concentration of chemical facilities and has faced challenges with fugitive and area source emissions, high ozone levels and community concerns about exposure to toxic air pollutants and odors associated with a nearby wastewater treatment facility. Measurements will focus on VOCs, hazardous air pollutants (HAPs), and potentially hydrogen sulfide (H_2S). This study will allow for testing Aeroqual sensor devices in near-source environments and evaluate community monitoring applications.

- *TROPOMI and TEMPO Satellite Projects*: EPA will participate field studies in which satellites will be launched into space to collect higher time resolution air quality measurements across the globe. Two of these studies include the Tropospheric Monitoring Instrument (TROPOMI; anticipated launch in 2016) and the Tropospheric Emissions: Monitoring of Pollution (TEMPO; anticipated launch in 2018/2019). These studies will rely on ground-based air quality measurement sites to validate the satellite measurements in which the AIRS and CAPABLE research sites are anticipated to serve in that capacity. Numerous sites will likely be needed to supplement the ground-based validation sites. Sensor technologies will play an important role as they can easily be distributed in a cost-effective manner to provide more spatial coverage.
- *Tower Based Studies*: Vertical measurements of air pollutants are lacking and needed to better characterize air quality and understand atmospheric chemistry throughout the day. These measurements are also important for air quality modeling applications. During the DISCOVER-AQ Earth Venture Mission, EPA placed sensor technologies along a 300-meter atmospheric observatory tower to measure air quality. This pilot application of sensors provided important information on differences in pollutants at varying heights in the atmosphere and helped to confirm observations from other collocated measurements. Funding dependent, EPA will to pursue similar tower based studies using sensor technologies.
- *Ozone Gardens*: Over the past few years, EPA has been collaborating with a number of institutions that have established a network of ozone gardens across the U.S. These gardens can be used as bioindicators for ozone exposure and contain ozone sensitive and ozone resistant plants paired with real-time, continuous ozone measurements. The widely used ozone monitoring instrument in these gardens costs about $6,000 (USD) and there is a strong desire to find lower-cost options to measure ozone levels. The gardens are used for both research and community engagement/educational purposes.
- *Wildfire Studies*: EPA has been investigating lower cost, easily deployable methods to measure emissions from wildfires. Wildfires represent special air pollution ‘events’ that are sporadic and contain high concentrations of pollutants including $PM_{2.5}$, CO, and carbon dioxide (CO_2). Low-cost sensors can provide a cost-effective and portable means to measure wildfire emissions rapidly that can inform state/local environmental agencies and neighboring populations of pollution levels.

All field deployments of sensor technologies will follow detailed Quality Assurance Project Plans (QAPPs) developed by EPA. Some of the QAPPs currently exist or will be developed to cover the research described under this CRADA project. If deemed necessary, an individual QAPP will be developed for this CRADA Project. The currently existing QAPP entitled “Methods Development, Evaluation and Applications for Ambient Air Criteria Pollutants, Key Precursor Species, and Meteorological Variables” [QAPP ID: D-EMMD-AQB-008-QAPP-01; approved on 4/6/2016] will apply to this CRADA and describes ambient measurement methods and procedures relevant to this project.

EPA Responsibilities:

The EPA shall deploy products from Aeroqual including but not limited to sensor devices and calibration equipment. The EPA support shall include deployment, set-up, calibration, daily operation and maintenance of sensor devices. The EPA shall provide traditional air quality measurement methods (e.g. FRM/FEM instruments or other methods) for comparison to the sensor technologies. As part of the overall deployment activities, EPA shall provide input on the design of Aeroqual products, calibration approaches, and user friendliness of the technologies. The EPA shall also evaluate the data and share the data with Aeroqual. The EPA shall develop QAPPs that cover the research conducted under this CRADA project as deemed necessary.

Aeroqual Responsibilities:

Aeroqual shall provide calibrated sensors and instruments to support sensor evaluation. Aeroqual and its U.S.-based distributors shall provide technical support and guidance on sensor deployment, operation, calibration and maintenance. Aeroqual shall ensure timely supply of replacement parts due to faults. Aeroqual shall also customize sensor devices and related products to facilitate evaluation of the sensor technologies. Aeroqual shall provide guidance on data evaluation and share data analysis outcomes with the EPA. Aeroqual shall provide information as needed to support development of EPA's QAPPs.

Task 2: Evaluating Design and Field Testing of Prototype Sensors for the Measurement of Criteria Pollutants and Air Toxics

Research Motivation**:** New and improved sensor devices and designs are continuously being developed by sensor manufacturers. The majority of commercially available sensors target measurement of criteria air pollutants (e.g. PM, NO_2, O_3, and others) and alternative methods for measuring those pollutants are being explored. A number of specific sensor applications such as fenceline/near-source monitoring and community/individual monitoring of sensors are driving demand for low-cost, portable technologies that measure pollutants of concern including volatile organic compounds (VOCs) and air toxics. Testing these newly developed devices in the field is critical to determine their performance in real-world conditions, calibration needs, and feasibility for different applications. Conducting replicate analysis of these technologies is also important to determine intercomparibility among the devices.

This task will allow for field investigation of prototype sensors including measurement capabilities, performance and calibration approaches for the measurement of criteria air pollutants and air toxics. Critical information about the data quality and other performance characteristics will be assessed. In addition to field testing, the design of the prototype sensor technologies will be evaluated and improvements will be made as necessary to optimize the sensor devices for different applications. This work will inform sensor research on the whole and can potentially infuse the sensor market with new approaches and methods for measuring specific air pollutants, increase understanding of the performance of these devices, and broaden understanding of potential applications of sensor technologies.

Method**s:** Prototype sensor devices that measure criteria air pollutants (e.g. PM, O_3, NO_2, SO_2) and air toxics (e.g. volatile organic compounds) are under development by Aeroqual. The design of the prototype devices will be evaluated and improvements in the technologies will be investigated and implemented as feasible. The data quality of the prototype sensors will also be evaluated to determine their applicability to various environmental questions. Cross-interference effects will be studied and mitigation strategies will be developed. Field evaluation opportunities will be similar to those described in Task 1 including:

- *Research Sites*: AIRS and CAPABLE sites
- *State/Local Regulatory Monitoring sites*: Raleigh Multi-Pollutant Site (state regulatory monitoring site)
- *Field studies*: Fenceline Monitoring Project in Louisville, Kentucky

Other field testing opportunities will be identified as feasible. Data collected from the prototype sensors will be compared to that measured by collocated traditional air quality methods, other research methods, each other, and/or similar low-cost measurement devices. Calibration methods will also be investigated as applicable.

EPA Responsibilities:

The EPA shall install and operate Aeroqual's prototype sensor devices. The EPA will supply reference grade methods (e.g. FRM/FEM analyzers) or other research methods for comparison and evaluation purposes. The EPA shall make site visits as necessary to maintain operation of the prototype sensor devices and retrieve data and useful metadata. The EPA shall conduct comparative data analysis and share the data with Aeroqual. As part of field deployments, EPA shall provide input on the design of Aeroqual products, calibration approaches, and user friendliness of the technologies. The EPA shall develop QAPPs that cover the research conducted under this CRADA project as deemed necessary

Aeroqual Responsibilities:

Aeroqual shall supply prototype sensor devices and all spares as well as calibration equipment to the EPA. Aeroqual and its U.S.-based distributors shall provide support and training to install and operate the prototype devices. Aeroqual shall assist with comparative data analysis using the EPA obtained data and metadata. Aeroqual shall provide information as needed to support development of EPA's QAPPs.

<u>Task 3: Communicating Results</u>

Research Motivation: This CRADA project will provide valuable information on the performance of existing and prototype sensor technologies and their potential applications. New sensor technologies, improvements in sensor design, and methods for calibration and operation will be developed and evaluated. As such, communicating the findings from this project will be critical for advancing knowledge in Next Generation Air Monitoring and Next Generation Emission Monitoring research and informing on how these technologies can be used in various applications.

Methods: The EPA and Aeroqual will jointly prepare the data generated from Tasks 1 and 2 for presentation at a scientific conference, publication in a peer-reviewed scientific journal, and/or publication of an EPA report.

EPA Responsibilities:

The EPA shall compile the data from sensor technologies used in the study. The EPA shall prepare publication materials. The EPA shall file patent protection documents if required prior to publication. The EPA shall also obtain any necessary publication authorizations and ensure that publications are properly routed through the Office of Research and Development publication clearance process.

Aeroqual Responsibilities:

Aeroqual shall assist in compiling the data from sensor technologies and preparing publication materials. Aeroqual shall file patent protection if required prior to publication. Aeroqual shall also obtain any necessary publication authorizations.

RESOURCES

The EPA and Aeroqual contributions, both non-monetary and monetary are described below.

EPA

The EPA will contribute technical assistance, logistical support and ambient air sampling and analysis. This will include use of EPA facilities, supplies, field work/sampling, and costs associated with their travel.

Estimated total in-kind contributions (USD): $700,000

Aeroqual

Aeroqual will provide sensors, instruments, technical assistance, data analyses and supporting research (including use of facilities, personnel and supplies), as needed.

Estimated total in-kind contributions (USD): $500,000
Estimated total cash contribution (if any): N/A

DELIVERABLES

Deliverables for this CRADA are summarized below. The parties will meet face-to-face at least annually to review the current work and to develop detailed plans for the next phases in order to implement the tasks outlined above. In addition, the parties will undertake quarterly conference calls to coordinate activities related to the project tasks. In the event of field deployments, the parties will have more frequent conference calls to discuss planning related to the projects.

Months 1 - 48 Task 1: Evaluating Design, Field Performance, and Calibration of Low-

Cost Sensor Devices

Months 12 - 48 Task 2: Evaluating Design and Field Testing of Prototype Sensors for the Measurement of Criteria Pollutants and Air Toxics

Months 12 - 60 Task 3: Communicating Results

The timeframe for deliverables and/or the scope of work outlined in this CRADA will be amended if deemed necessary by the EPA and Aeroqual to ensure success of this project.

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